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OPTIMIZING THE COMBINATION OF STRENGTH AND STRESS-CORROSION RESISTANCE OF 7075 ALUMINUM BY THERMAL-MECHANICAL TREATMENTS

Final Report

(15 September 1968 through 15 March 1969)

April 1969

By

A. J. Jacobs

Prepared Under Contract No. N00019-68-C-0433

for

Naval Air Systems Command
Department of the Navy

By
Rocketdyne
A Division of North American Rockwell Corporation
Canoga Park, California

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FOREWORD

This report was prepared by the Chemical and Material Sciences organization of the Research Division of Rocketdyne, a Division of North American Rockwell Corporation, in compliance with Contract No. N00019-68-C-0433, Naval Air Systems Command, U. S. Navy, covering the period from 15 September 1968 through 15 April 1969. The contract monitor was Mr. R. Schmidt.

The principal investigator was Dr. A. J. Jacobs with Dr. W. T. Chandler providing technical supervision. The contributions of Dr. R. P. Jewett, who was responsible for thin-film microscopy; Mr. J. Testa, who performed the conventional metallographic work; and Mr. G. Dyer, who assisted in a general way with the experimentation, are gratefully acknowledged.

This document has been assigned Rocketdyne Report No. R-7822.

ABSTRACT

Overaged 7075 aluminum alloy, possessing inherently high resistance to stress-corrosion cracking, was forged or rolled to re-gain the strength lost by overaging. The reductions that would be required were over-estimated, so that excessively thick sections were used as starting material. Forging was much more effective than rolling in achieving uniform strengthening, and was more effective at longer than at shorter overaging times. The maximum strength obtained by forging in the center of a 4-inch-thick starting block, which had been overaged for 20 hours at 350 F, was ~62000 psi (compared to ~57000 psi for the starting block). Neither forging nor rolling of overaged 7075 caused any failures within a 30-day test period.

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INTRODUCTION

The objective of an earlier Rocketdyne program with the Naval Air Systems Command was to determine the mechanism of stress-corrosion cracking in 7075 and related aluminum alloys. The objective of the program reported upon herein was to apply the knowledge and improved understanding of the stress-corrosion mechanism so gained to the optimization of properties of these alloys.

It is well known that the age hardening of aluminum alloys is associated with a decrease in stress-corrosion resistance. The mechanistic phase of the earlier program showed that this decrease is most pronounced when the aging is accelerated by a prior mechanical treatment. Furthermore, it has been shown that age hardening is more detrimental to stress-corrosion resistance than is strain hardening. It has become clear that a certain amount of strain hardening is required if an optimum combination of strength and stress-corrosion resistance is to be achieved. Strain hardening is most beneficial when carried out subsequent to all aging operations and on well overaged material. Performed in this manner, the strain hardening does not induce additional aging, such as it does in an underaged condition (relative to -T6), in -T6 itself, or in a slightly overaged condition (relative to -T6).

To meet the stated objective, several overaged conditions of the 7075 alloy possessing inherently high stress-corrosion resistance were deformed to increase the strength properties. Two conventional methods of deformation were investigated, viz., forging and rolling. Tensile and stress-corrosion tests were conducted to determine the thermal-mechanical treatment producing the best combination of yield strength and stress-corrosion resistance. A yield strength of 69100 psi and a stress-corrosion time-to-failure exceeding 30 days had already been achieved by explosively shock loading 7075-T73 (Ref. 1).

EXPERIMENTAL PROCEDURE

MATERIAL

The starting material for this study consisted of seven hand-forged 7075-T73 billets, each billet measuring 4 by 6 by 8 inches, and each conforming to MIL SPEC A-22771-B. Six of the billets originated from the same heat (No. W11994). The composition of these six plus that of the seventh which came from another heat (No. W11657) are shown in Table I. Representative tensile properties reported by the supplier (Weber Metals and Supply Co.) appear in Table II. The reported electrical conductivities were 40.5% IACS (Heat No. W11994) and 38.5% IACS (Heat No. W11657).

HEAT TREATMENT

Four of the as-received billets were sectioned, as shown in Figure 1, for heat treatment and subsequent forging; and three were sectioned, as shown in the same figure, for heat treatment and subsequent rolling. Each piece was solution heat treated at 895 F for 5 hours, water quenched, and the material converted to the -T6 temper by aging at 250 F for 24 hours. The final heat treating step was an overaging treatment performed at 350 F. The billets for forging, designated by AF, BF, and CF were overaged for 50, 150, and 400 hours, respectively. One half of billet DF (Figure 1) was overaged for 20 hours and the other half for 35 hours. The billets for rolling, AR, BR, and CR, were heated for 50, 150, and 400 hours. All heating times were measured from the time the material had reached temperature.

MECHANICAL WORKING

Forging

Forging was carried out at a local shop (Carlton Forge Works) using a United 1500-ton steam hydraulic press. Preheat in a 300 F furnace

TABLE I

COMPOSITION OF 7075 STARTING MATERIAL
(REPORTED BY SUPPLIER)

Heat No.	Weight Percent								
	Zn	Mg	Cu	Fe	Cr	Si	Mn	Ti	Al
W11994	5.51	2.53	1.80	.25	.20	.07	.02	.02	Bal.
W11657	5.74	2.48	1.66	.30	.20	.11	.03	.03	Bal.

TABLE II

TENSILE PROPERTIES OF 7075 STARTING MATERIAL

(REPORTED BY SUPPLIER)

Heat No.	Direction	Yield Strength (psi)	Tensile Strength (psi)	Elongation (% in 1.4 in.)
W11994	Longitudinal	58700	71150	13.6
	Long Transverse	56450	69150	10.0
	Short Transverse	57300	67600	5.0
				Elongation (% in 2 .)
W11657	Longitudinal	59100	71100	11.4
	Long Transverse	59800	72300	10.7
	Short Transverse	56000	71000	6.4

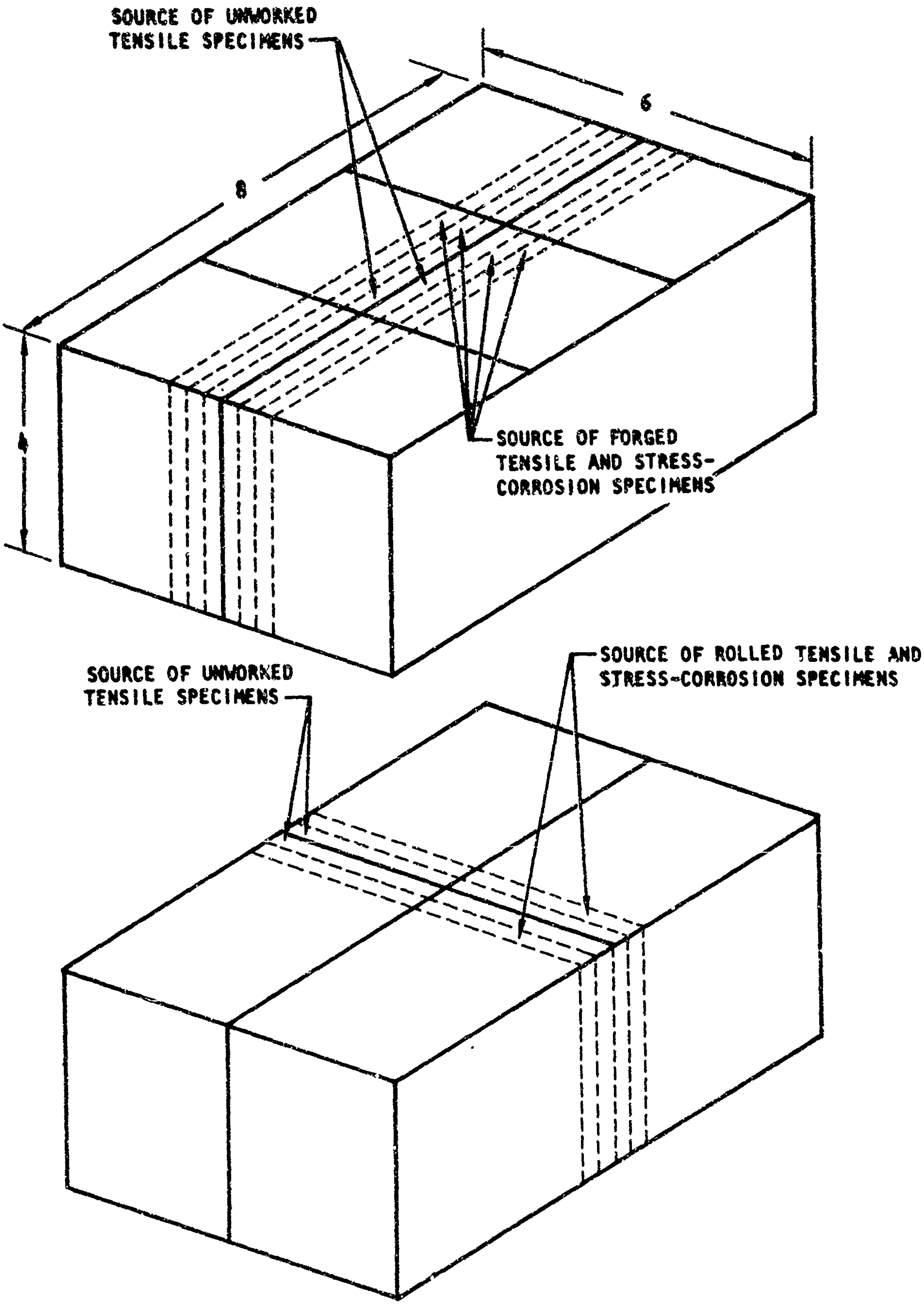


Figure 1. Sectioning of As-Received 7075-T73 Hand Forgings for Heat Treatment and Forging (Billets AF, BF, CF, DF) or Rolling (Billets AR, BR, CR).

was necessary to prevent cracking in all but the most highly overaged condition (CF). The individual blocks from each billet were compressed once in the short transverse and once in either the longitudinal or long transverse directions. The reductions in area that were obtained are listed in Table III. Photographs of the forged blocks are shown in Figure 2; the blocks are oriented as they were in the original forgings.

Rolling

The rolling was performed at the Atomics International Division of the North American Rockwell Corporation. A two-high mill having 18-in.-diameter rolls and manufactured by the Farrel Foundry and Machine Company was used in the operation. The starting blocks shown schematically in Figure 1 were oversize for the 3-in. roll gap, so they were machined to give a 3-in. by 3-in. transverse (short transverse by long transverse) cross section. Passes were made in the original longitudinal direction. The blocks were preheated in a 300 F furnace and returned to the furnace as required during the rolling. The final long transverse dimension (in the end section) was maintained close to 3 inches. Therefore, the reductions in area (of the end sections) were proportional to the reductions in the short transverse dimension (Table IV). The rolled blocks can be seen as originally oriented in the photographs of Figure 3. No cracking was encountered in the rolling.

PROPERTY MEASUREMENTS

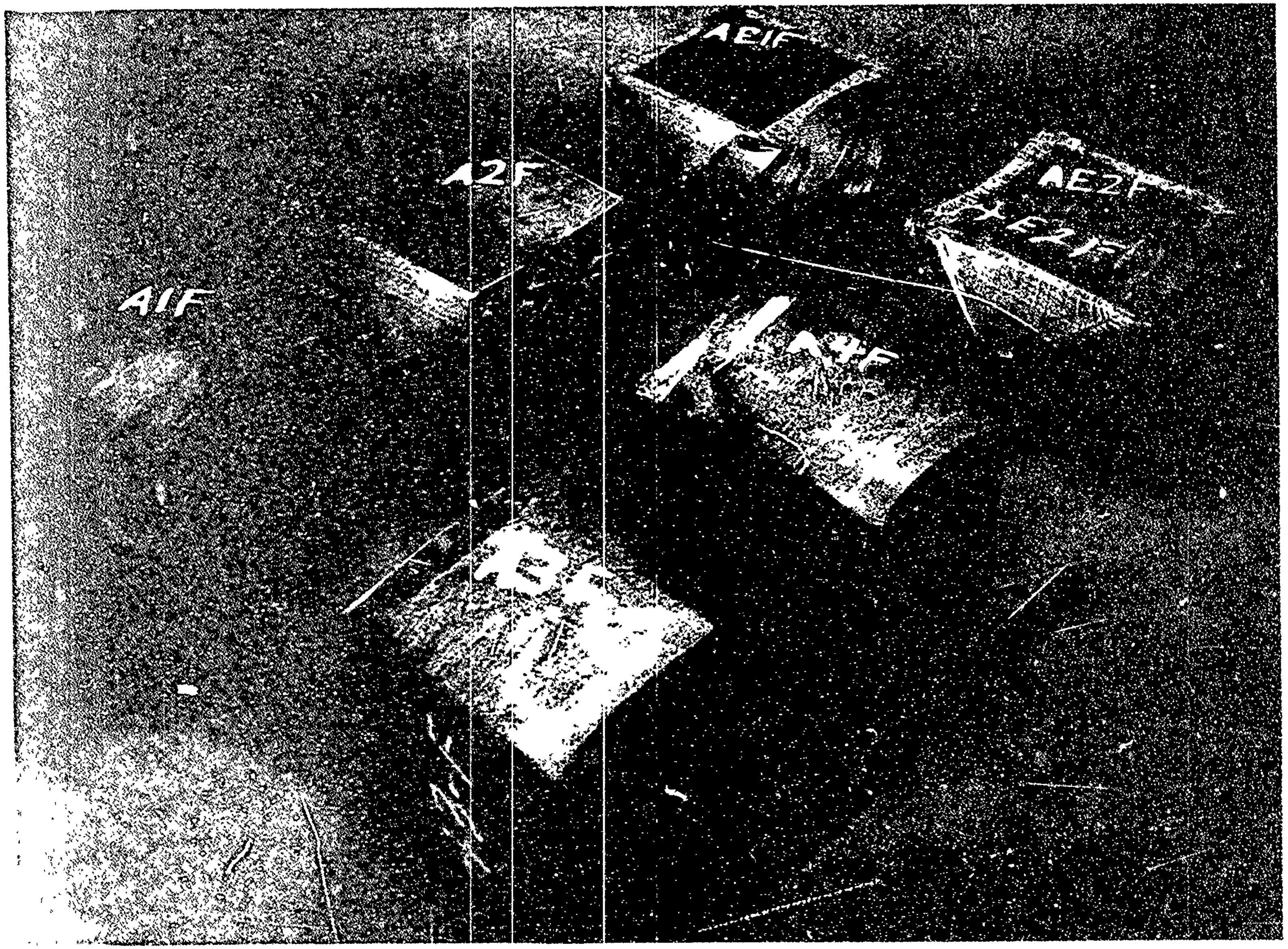
Tensile and Stress-Corrosion Tests

The tensile and stress-corrosion specimens were machined with their axes in the short transverse direction of the billet and were

TABLE III

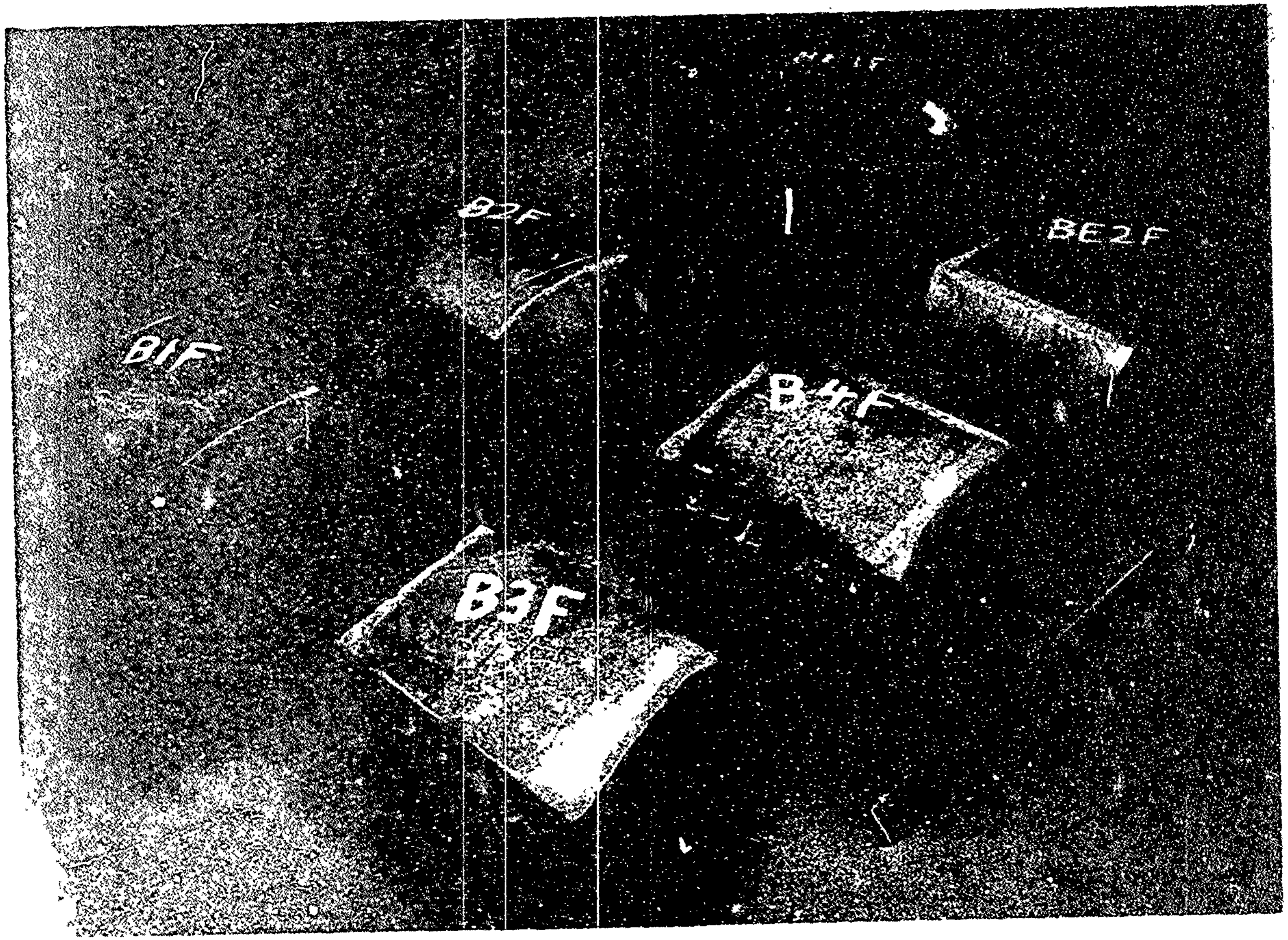
REDUCTIONS IN AREA OBTAINED BY PRESS FORGING OVERAGED 7075

Billet	Overaging Time at 350 F (hrs.)	Block	Cold(C) or Warm(W) Forging	Cracking	% Reduction in Area	Hardness Survey
DF	20	D3F	W	No	7	Yes
		D1F	C	Yes	10	
		D2F	W	Yes	10	
	35	D4F	C	No	10	
		D6F	W	No	15	
		D5F	W	Yes	16	
AF	50	A1F	W	No	20	Yes
		A3F	W	No	23	
		A2F	W	Yes	30 (attempted)	
		A4F	W	Yes	40 (attempted)	
		AE1F	C	Yes	50 (attempted)	
		AE2F	C	Yes	50 (attempted)	
BF	150	B1F	W	No	17	
		BE1F	C	No	22	
		B2F	W	No	25	
		B3F	W	No	28	
		B4F	W	No	30	
		BE2F	C	Yes	40 (attempted)	
CF	400	C1F	W	No	20	Yes
		C2F	W	No	25	
		C4F	W	No	30	
		C3F	W	No	31	
		CE2F	C	No	36	Yes
		CE1F	Not Forged	--	--	



5AG23-11/12/68-C1C

Figure 2. Forged Blocks from Overaged Billet AF.

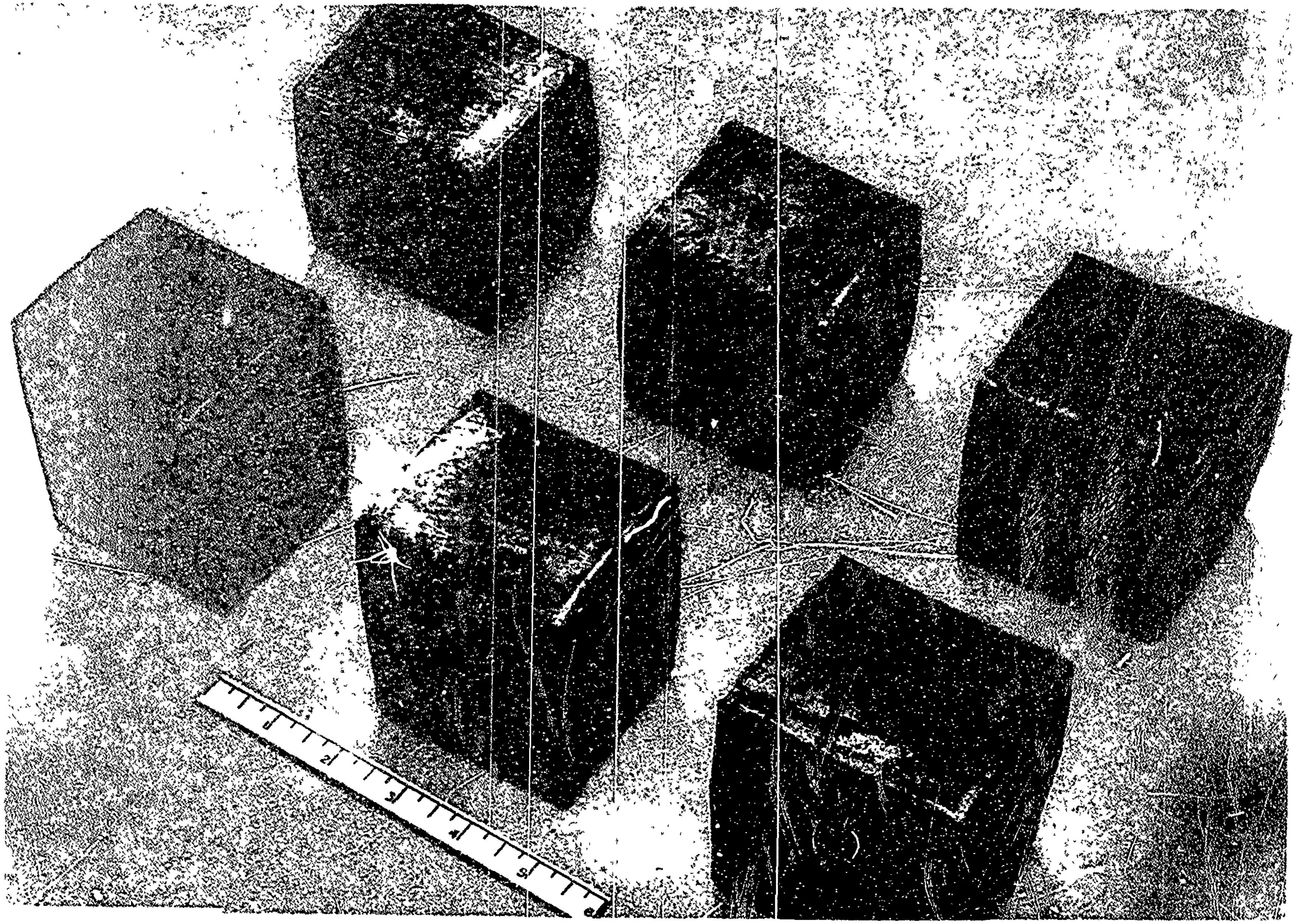


5AG23-11/12/68-1B

Figure 2. Forged Blocks from Overaged Billet BF.

5AG23-11/12/58-C1A

Figure 2. Forged Blocks from Overaged Billet CF.



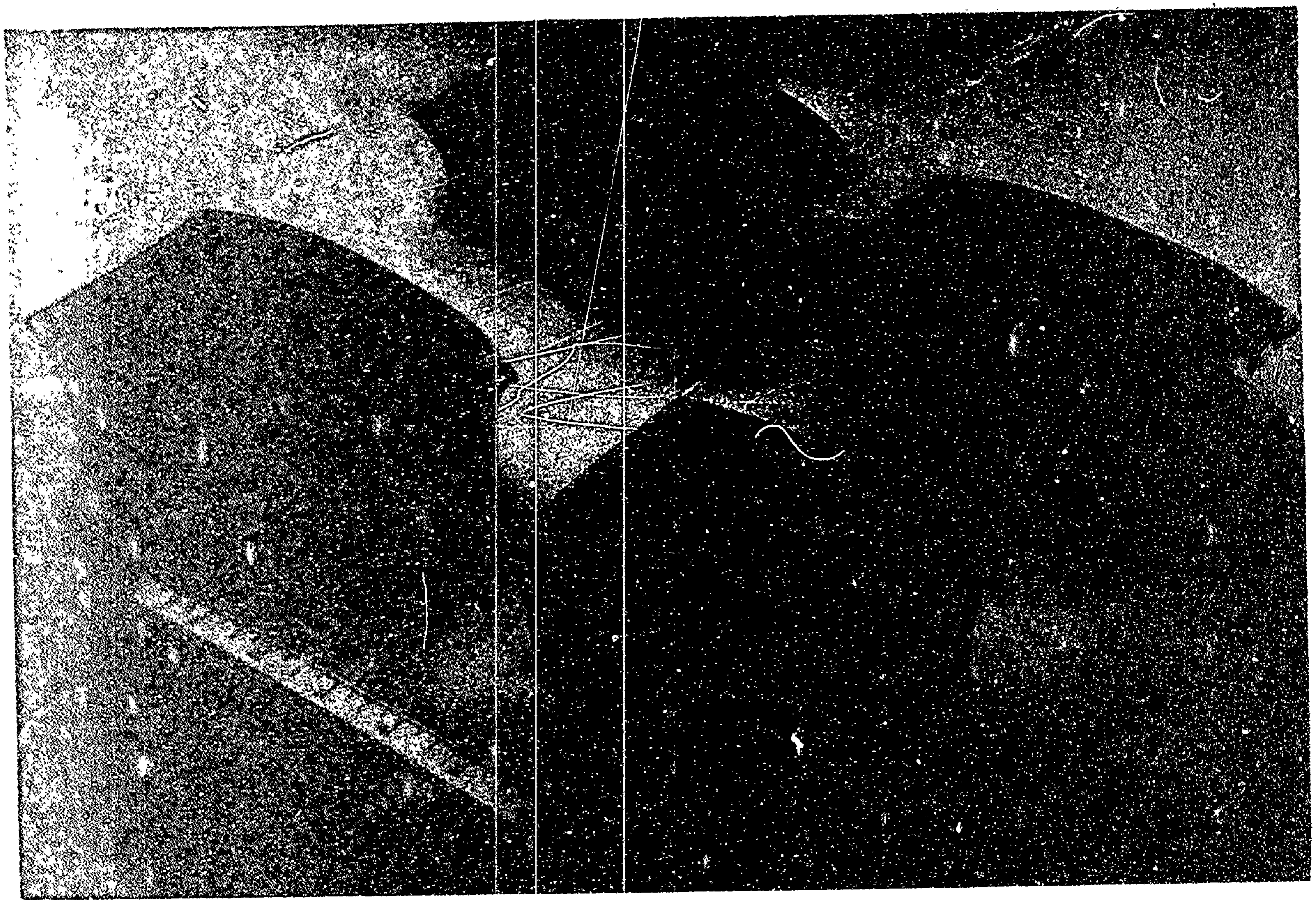
5AG86-12/16/68-C1

Figure 2. Forged Blocks from Overaged Billet DF.

TABLE IV

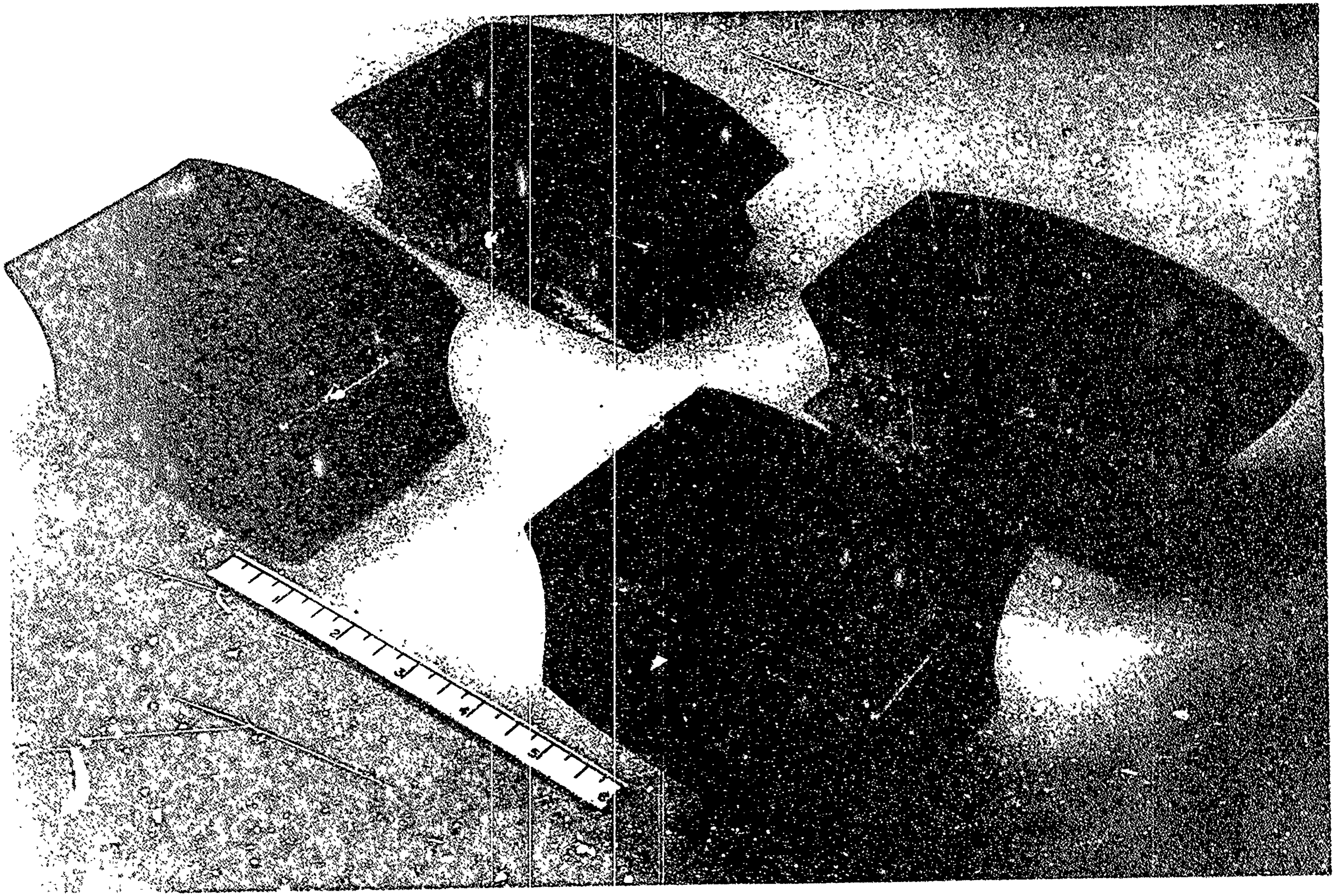
REDUCTIONS IN AREA OBTAINED BY
ROLLING OVERAGED 7075

Billet	Overaging Time at 350 F (hrs.)	Block	% Reduction in Area	Hardness Survey
AR	50	A1R	6	Yes
		A2R	14	
		A3R	21	
		A4R	27	Yes
BR	150	B1R	7	Yes
		B2R	14	
		B3R	23	
		B4R	28	Yes
CR	400	C1R	8	Yes
		C2R	17	
		C3R	27	
		C4R	28	Yes



5AG15-1/3/69-C1C

Figure 3. Rolled Blocks from Overaged Billet AR.



5AG15-1/5/69-G1F

Figure 3. Rolled Blocks from Overaged Billet BR.

5AG15-1/3/69-C1A

Figure 3. Rolled Blocks from Overaged Billet CR.

centrally located with respect to the upper and lower billet surfaces. A typical specimen is shown schematically in Figure 4 and the general locations of the specimens in the billets in Figure 1.

Tensile tests on control, i.e., unworked, specimens were conducted in duplicate, except in the case of billet DF where they were conducted in triplicate for each of the two (20- and 30-hour) overaging treatments. The tests on worked specimens were run in duplicate.

Stress-corrosion tests were of the alternate-immersion type and were conducted in an aqueous 3½% NaCl solution. The tests on the worked specimens were performed in duplicate at the 75%-of-yield stress level. Because of the expected high stress-corrosion resistance of the unworked material, control tests were not conducted.

Hardness Tests

Hardness surveys were made over the thickness (i.e., short transverse direction) of selected forged or rolled blocks to determine the extent of hardening at various depths below the surface. One-quarter-inch thick plates, which were oriented parallel to the longitudinal direction of the forged blocks and to the transverse direction of the rolled blocks, were machined from the center of these blocks. Superficial Rockwell measurements (30-T scale) were made at 1/4-inch intervals starting at 1/8-inch from one surface. The blocks that were selected for the surveys are so designated in the last columns of Tables III and IV. The baseline hardness properties of the overaged but unworked material were established using blocks A2F, B2F, C2F, A2R, B2R, C2R, D1F, and D4F. Sixteen to eighteen measurements were made on each of these blocks.

METALLOGRAPHY

Light Microscopy

Specimens for light microscopy were prepared from forged blocks C1F

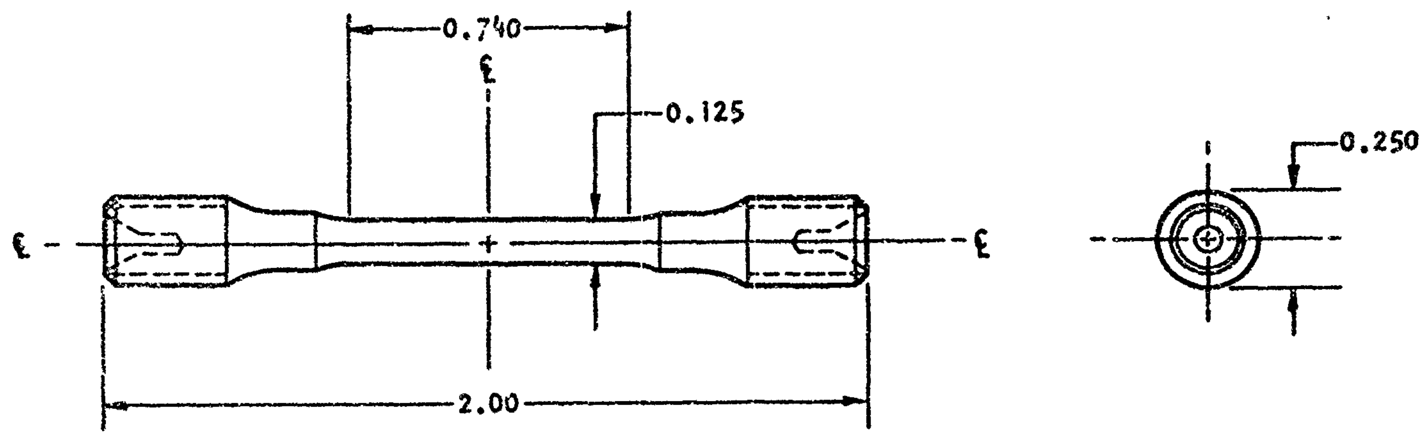


Figure 4. Typical Specimen Used for Tensile and Stress-Corrosion Testing.

and CE2F and from rolled block C4R. Specimens from the forged blocks lay in three mutually perpendicular planes formed by the longitudinal and transverse directions of the billet. Two specimens, both lying in the rolling plane, were examined from block C4R. One came from the top of the block and the other from the middle. Standard chemical polishing and etching techniques were used.

Thin-Film Microscopy

Thin films were prepared from the same forged and rolled blocks as were the light microscopy specimens. The planes of films from blocks C1F and CE2F were formed by major billet directions. The films from block C4R were more randomly oriented. The electro-polishing procedures and electron microscope have been described elsewhere (Ref. 2).

EXPERIMENTAL RESULTS

FORGING

Mechanical Property Changes

The yield and tensile strengths of the forged material are shown plotted against overaging time in Figure 5 and against percent reduction in area (% RA) of the forged block in Figure 6. The ductility, as measured by % RA and percent elongation, is plotted against % RA of the forged block in Figure 7.

It is seen in Figure 5 that the forging has imparted appreciable strengthening to the overaged material. The maximum increment in yield strength (10.4 ksi) occurs at an overaging time (t) of 50 hrs. This increment diminishes to 4.8 ksi at t = 20 hrs. and to 8.4 ksi at t = 400 hrs. Also at t = 20 hrs. and t = 400 hrs., there is little or no increment in tensile strength. The maximum increment in tensile strength, at a given overaging time, is always less than the corresponding increment in yield strength and increases from 3.0 ksi at t = 35 hrs. to 4.4 ksi at t = 150 hrs.

The most significant change in strength with forging reduction is a decrease in yield strength, which occurs above ~25% RA for billets BF and CF (Figure 6). The possibility that these decreases signaled the onset of recrystallization was checked metallographically (see "Light Microscopy" section).

Although not enough data points were obtained to be certain, there seems to be a tendency for the ductility to decrease up to a critical level of forging reduction and then to increase (Figure 7). The reduction in area reaches the control value sooner than does the elongation. There is also an indication that the minimum ductility occurs at smaller forging reductions, the shorter the overaging time, which is what

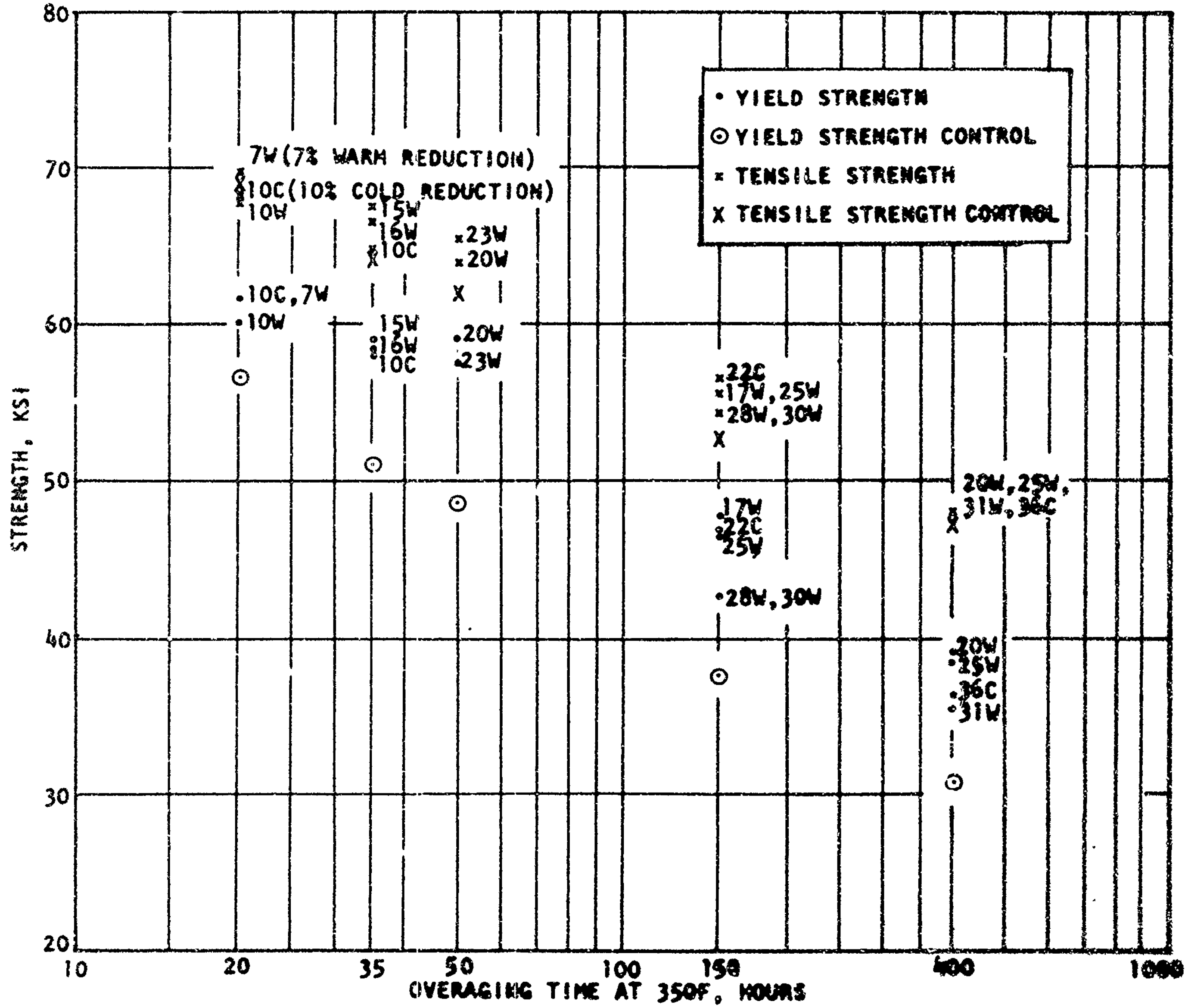


Figure 5. Yield and Tensile Strengths of Overaged-and-Forged 7075 Shown Plotted As a Function of Overaging Time at 350 F.

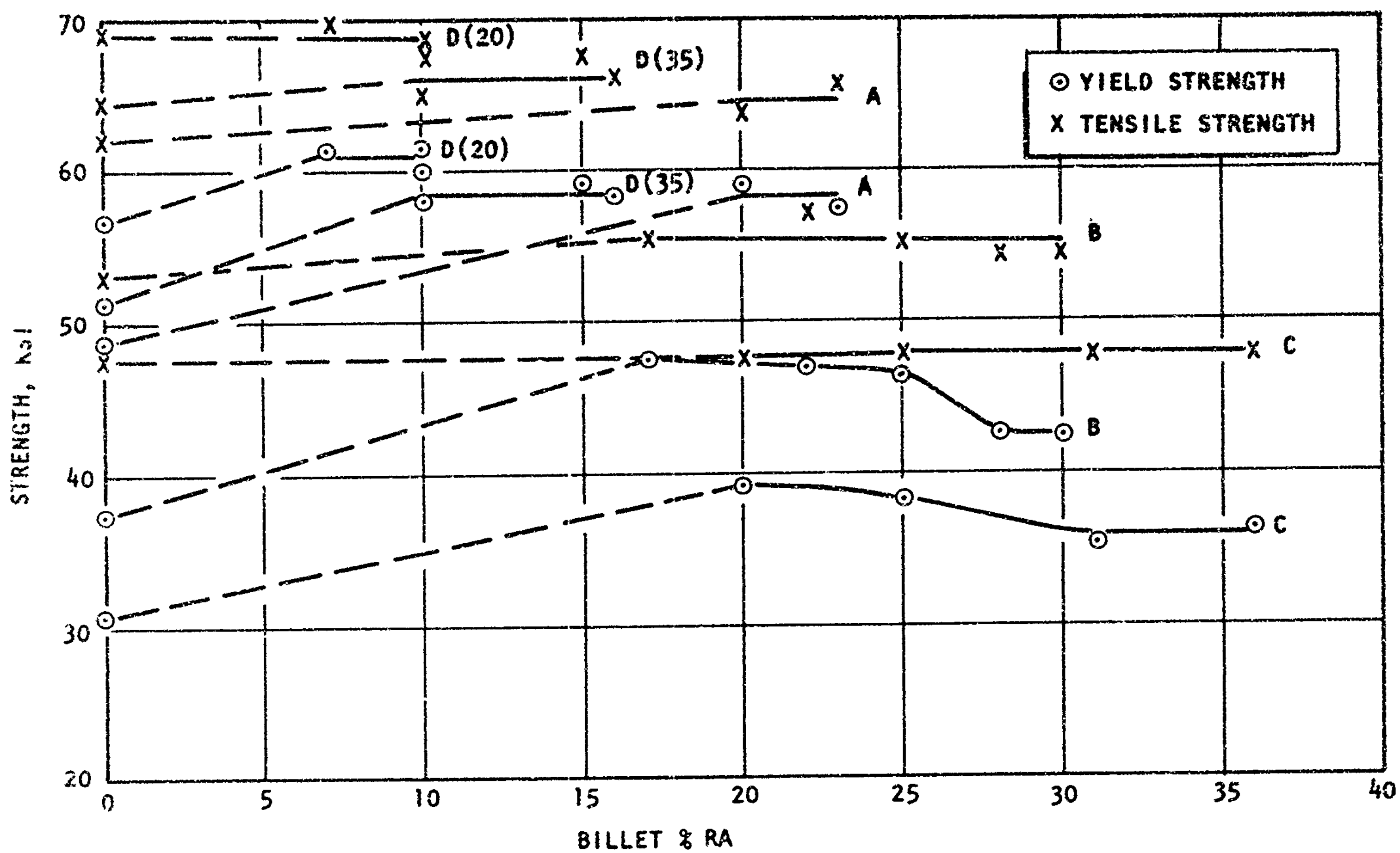


Figure 6. Yield and Tensile Strengths of Overaged-and-Forged 7075 Shown Plotted As a Function of Forging Reduction.

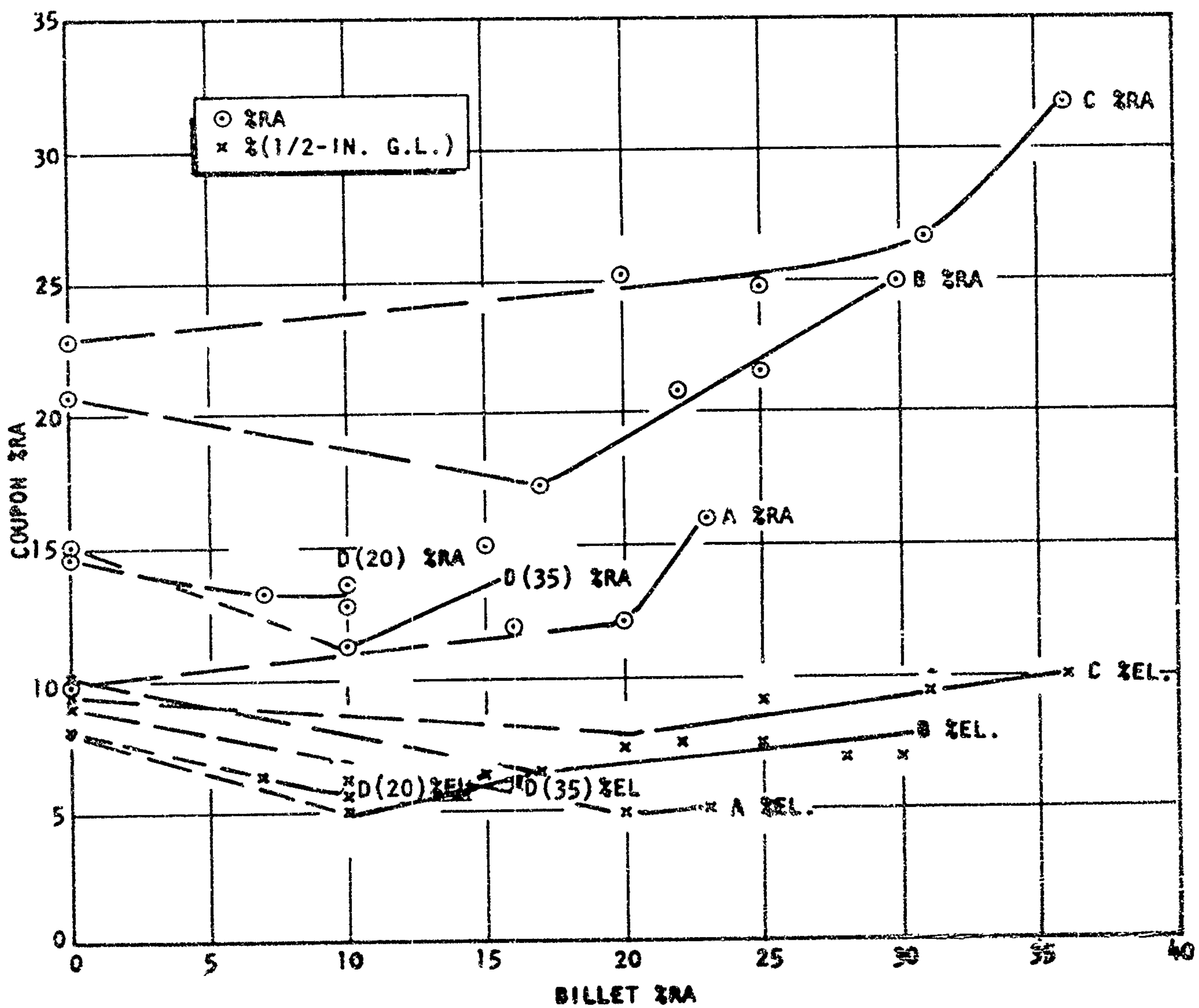


Figure 7. Ductility of Overaged-and-Forged 7075 Shown Plotted As a Function of Forging Reduction.

one might expect if the minimum coincided with the start of recrystallization. For billets BF and CF, the minimum ductility occurs at less than 25% forging reduction, which is where the yield strength underwent its largest decrease.

As indicated by the areas which are bounded above and below by the hardness vs. depth curves and the baseline hardness values, respectively, in Figure 8, maximum hardening was obtained in block C1F. Maximum strengthening was achieved in A1F, however (Figure 5). The same curves (cf. C1F and A1F in Figure 8) suggest that in-depth hardening (barring possible recrystallization phenomena) is favored by a longer overaging time.

Stress-Corrosion Property Changes

No failures were obtained within a 30-day testing period. The tests were terminated at the end of this time.

Metallography

Light Microscopy. In the section, "Mechanical Property Changes," the yield strength results indicated that recrystallization may have occurred in block CE2F (36% RA) but not in C1F (20% RA). Thus these blocks were selected for metallographic examination.

Two sets of micrographs are shown in Figure 9. The first set represents block C1F, and the second CE2F. Each set contains three mutually perpendicular orientations designated by a, b, and c. Possible microscopic evidence for recrystallization in CE2F was found in the "b" orientation, as seen in the figure. The only other difference that could be detected in the microstructures of C1F and CE2F was observed in the "a" orientation. The grain structure appeared more elongated in CE2F because of the 16% greater reduction and because CE2F was compressed in the short and long transverse directions instead of in the short transverse and longitudinal directions as was C1F.

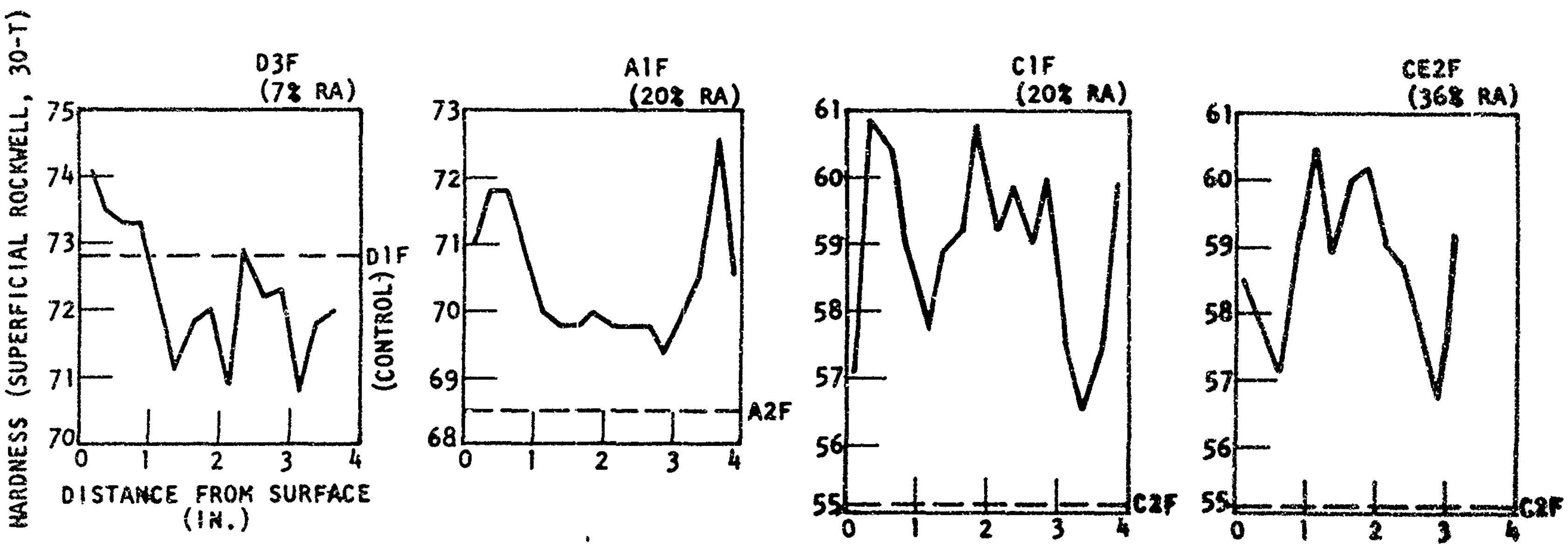
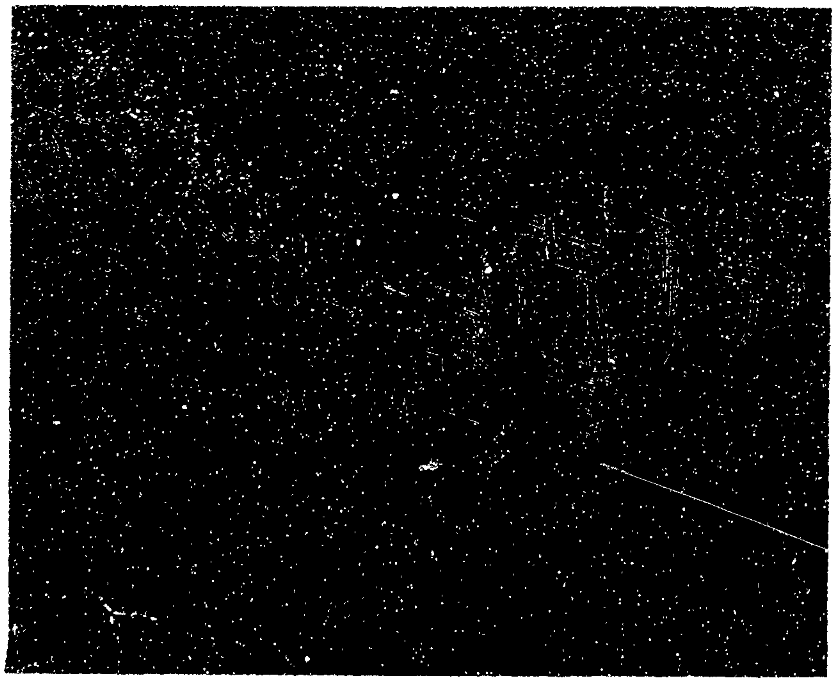
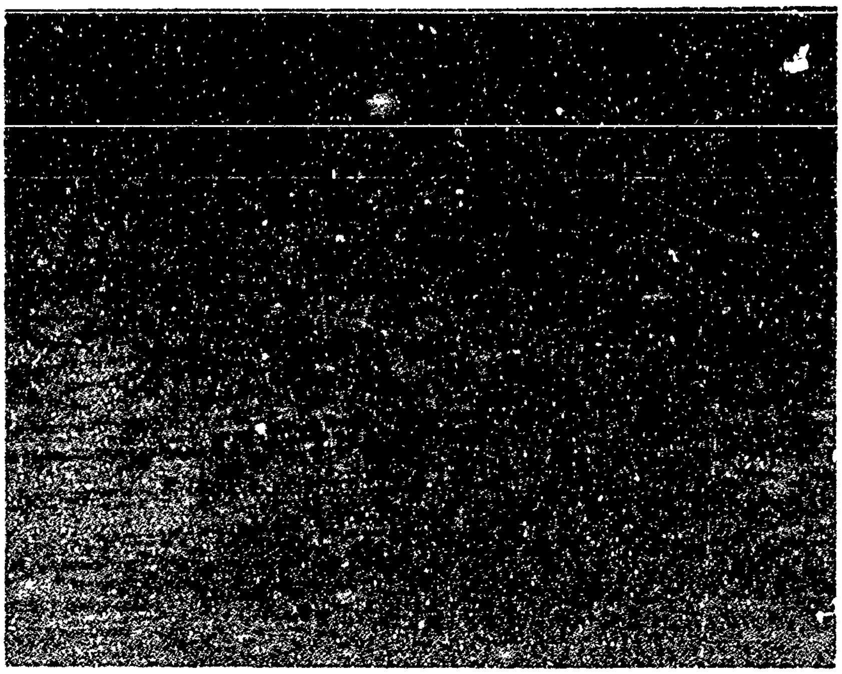


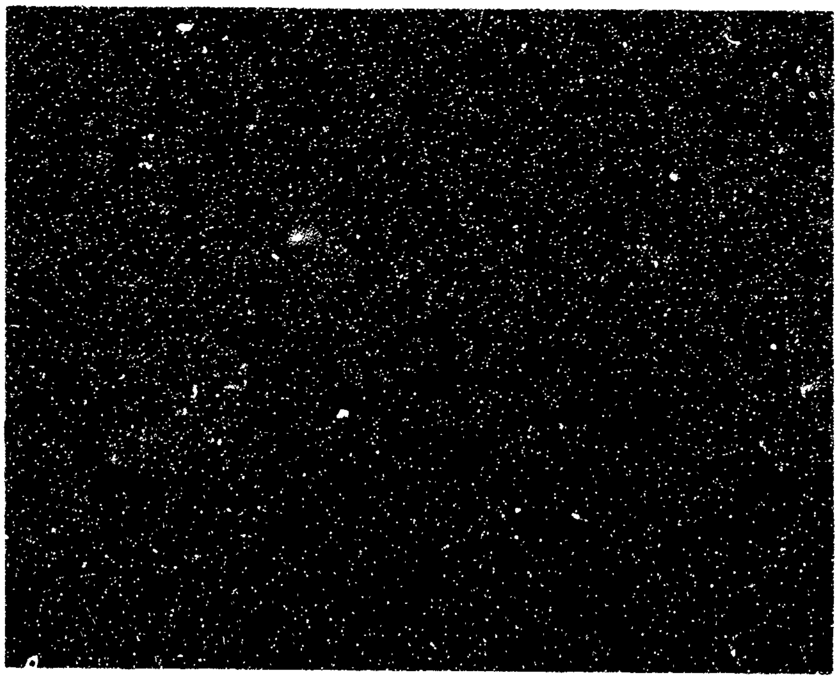
Figure 8. Results of Hardness Surveys Over the Thickness of Selected Overaged-and-Forged 7075 Blocks.



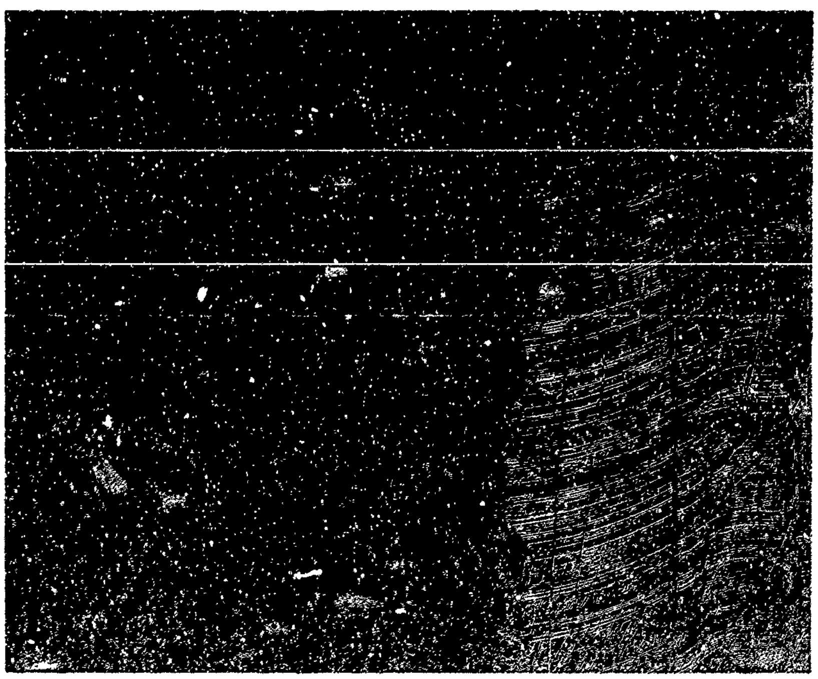
Block C1F
Orientation a



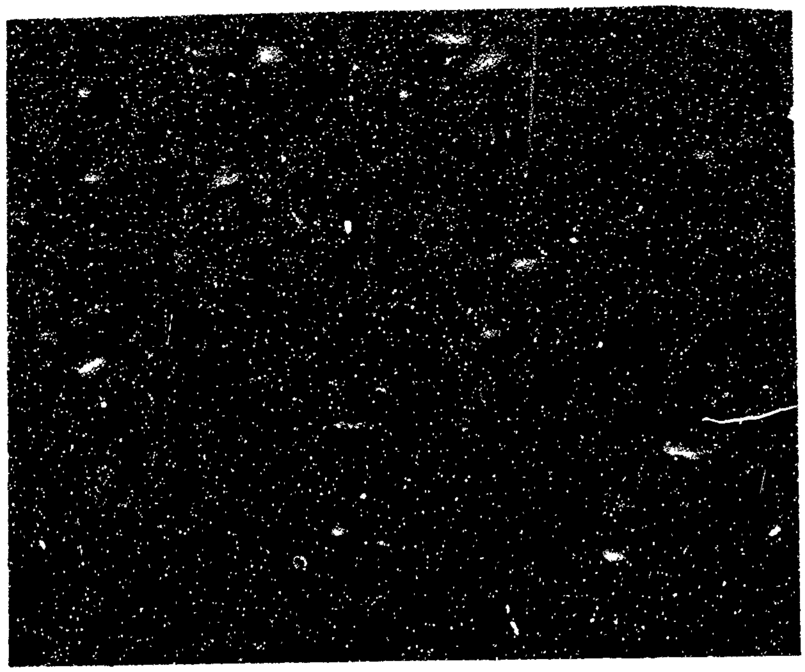
Block CE2F
Orientation a



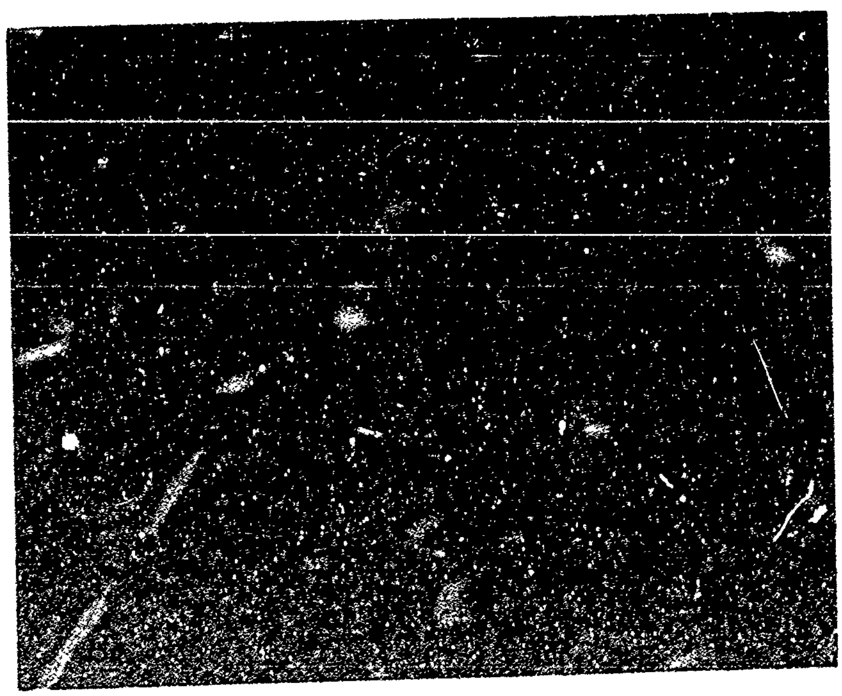
Block C1F
Orientation b



Block CE2F
Orientation b



Block C1F
Orientation c



Block CE2F
Orientation c

Figure 9. Light Micrographs of Overaged-and-Forged 7075 Alloy (Etchant 2 Vol. % Aq. HF; Magnification 200X).

Thin-Film Electron Microscopy. The thin films prepared from blocks C1F and CE2F were similar in appearance. As shown by a typical electron micrograph taken of C1F (Figure 10), there is a considerable proportion of elongated precipitate particles (probably $MgZn_2$). Dislocations produced by the forging are difficult to resolve. It is unlikely that dislocations could escape from a thin film containing such a high density of precipitate particles.

ROLLING

Mechanical Property Changes

The rolling operation did not effect any changes in the tensile properties of the blocks at the particular depth where measured. The tensile specimens, it should be recalled, were aligned in the short transverse direction and were centrally located with respect to the upper and lower billet surfaces. Figure 11 shows a plot of strength vs. overaging time and Figure 12, a plot of strength vs. % RA of the rolled block. A large degree of scatter is apparent in the ductility measurements (Figure 13), especially those involving reduction in area.

The hardness data, which are plotted in Figure 14, indicate that maximum integrated hardening as well as the most uniform hardening was obtained in block B4R. This is the only block of those selected for measurement which shows significant internal hardening.

Stress-Corrosion Property Changes

No failures occurred within the 30-day test period.

Metallography

Light Microscopy. Because rolling had no effect upon strength properties measured away from the rolling surfaces, a light microscopy

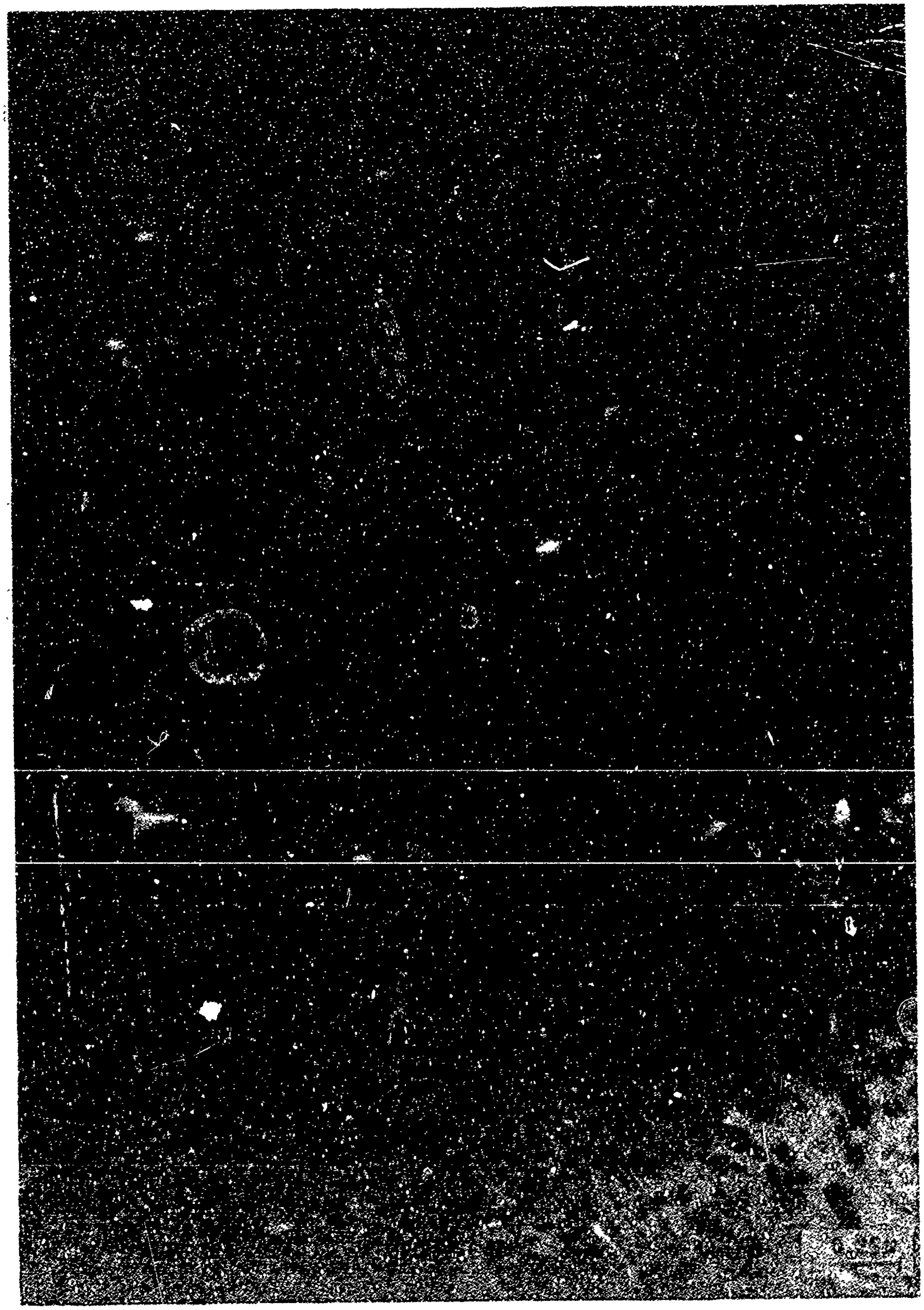


Figure 10. Thin Film Electron Micrograph of Overaged-and-Forged 7075 (Block C1F).

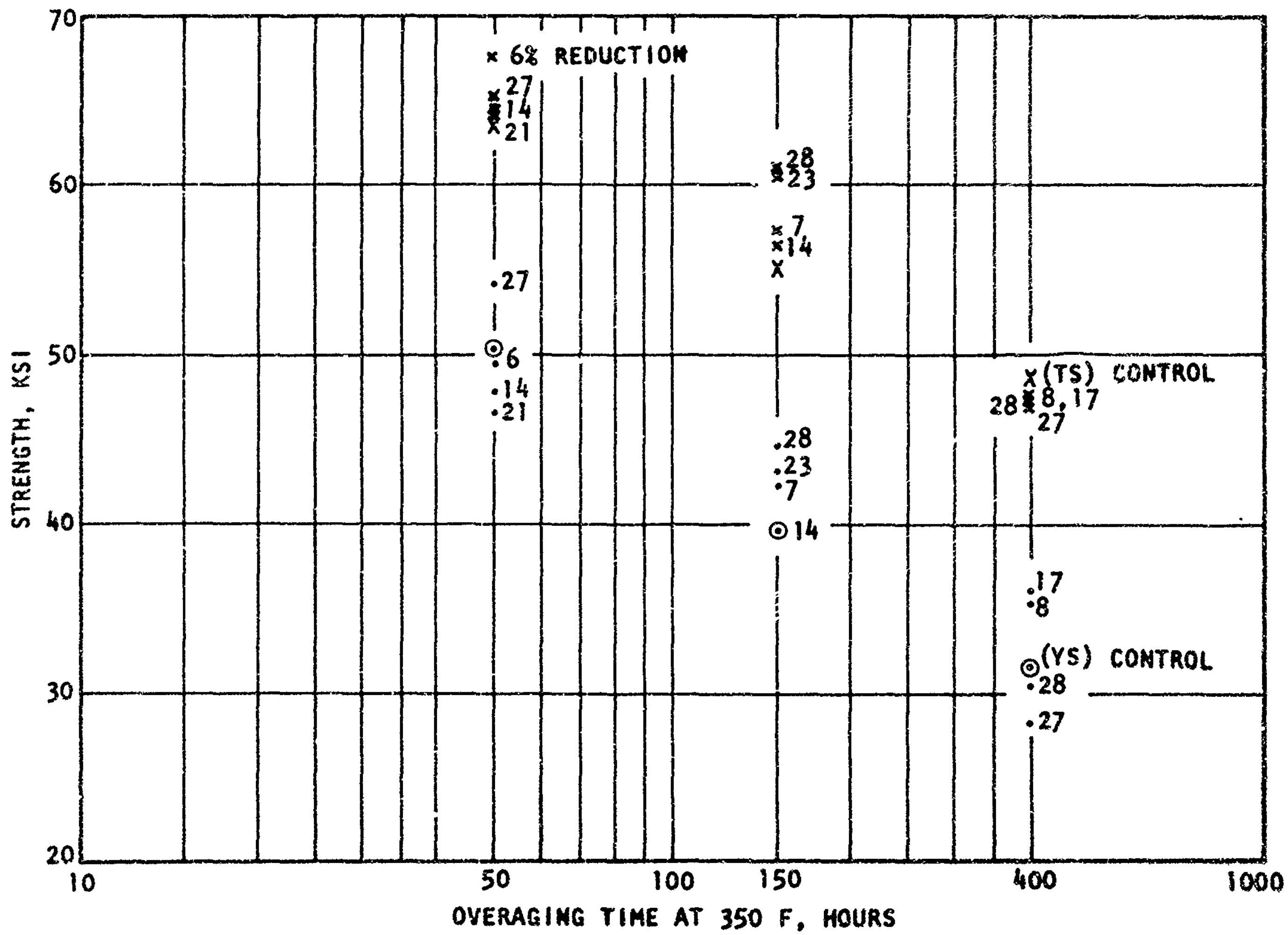


Figure 11. Yield and Tensile Strengths of Overaged-and-Rolled 7075 Shown Plotted As a Function of Overaging Time at 350 F.

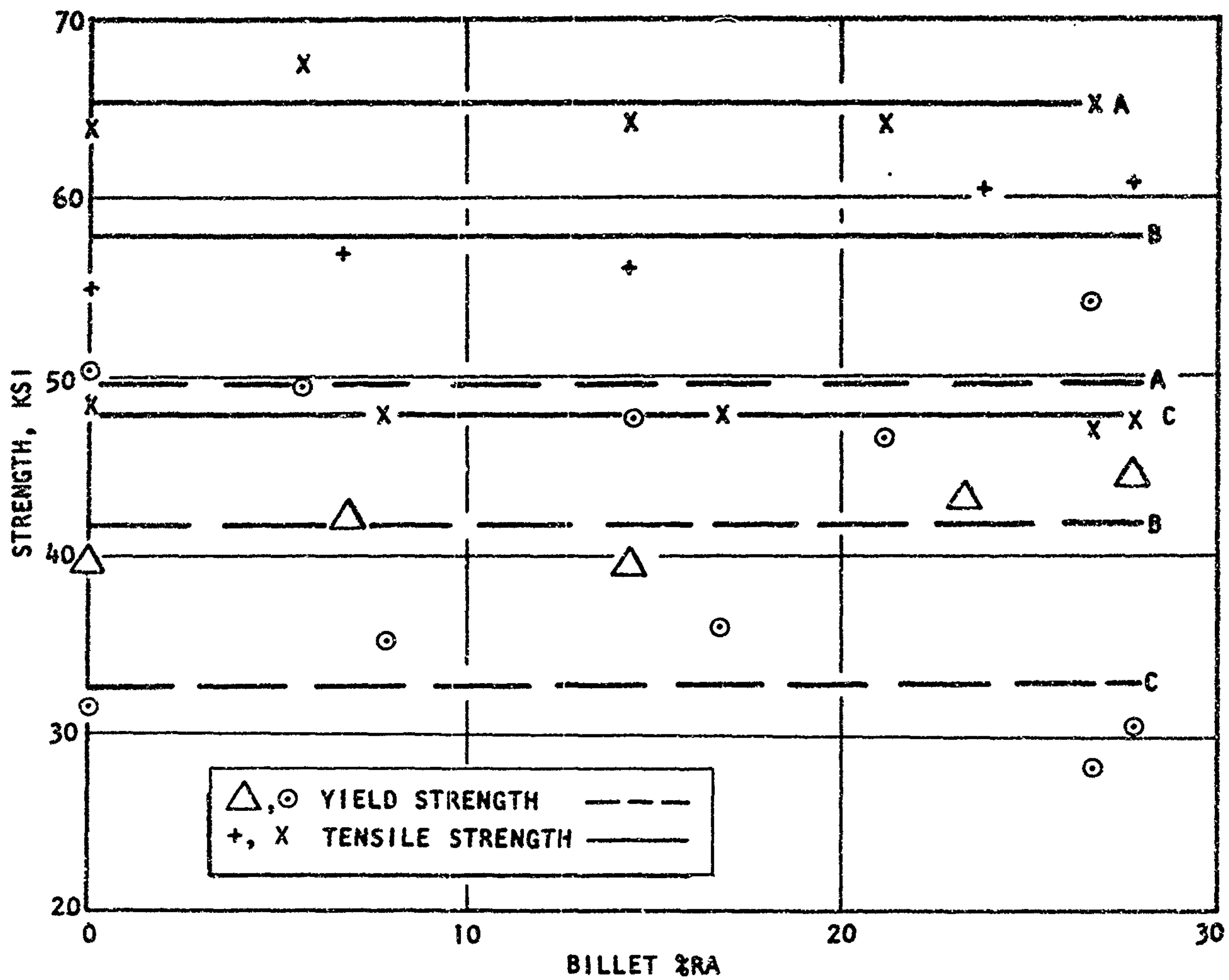


Figure 12. Yield and Tensile Strenghts of Overaged-and-Rolled 7075 Shown Plotted As a Function of Rolling Reduction.

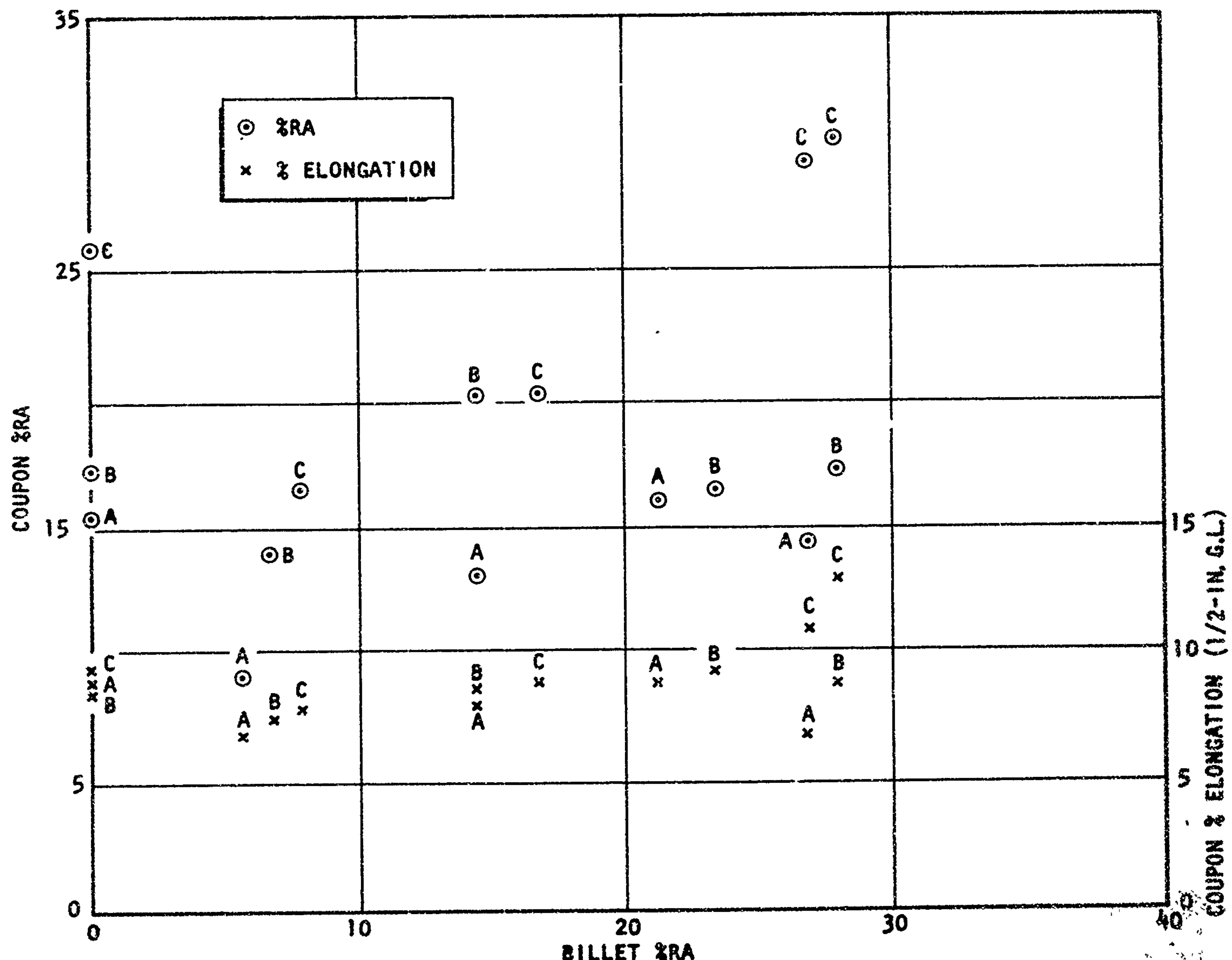


Figure 13. Ductility of Overaged-and-Rolled 7075 Shown Plotted As a Function of Rolling Reduction.

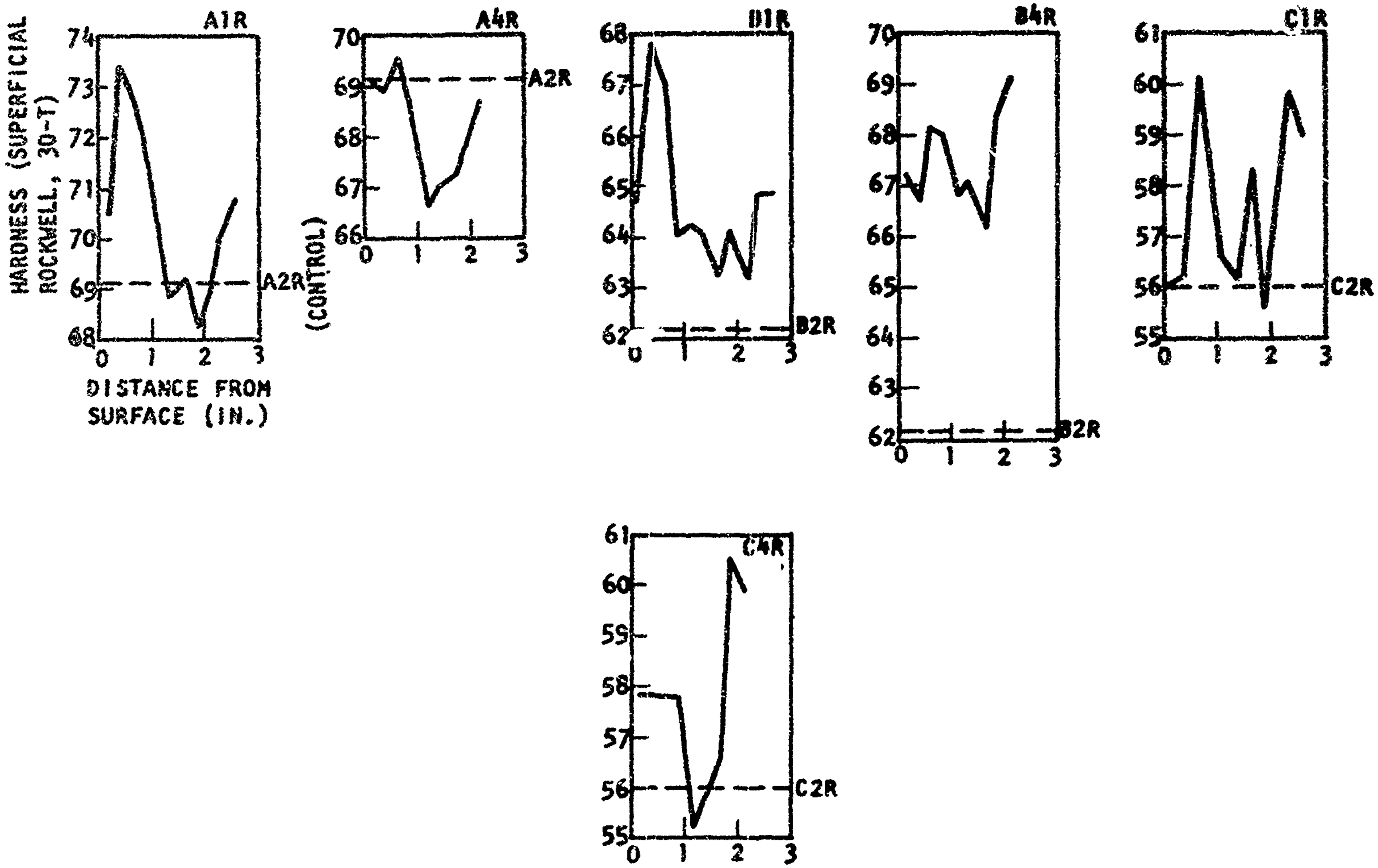
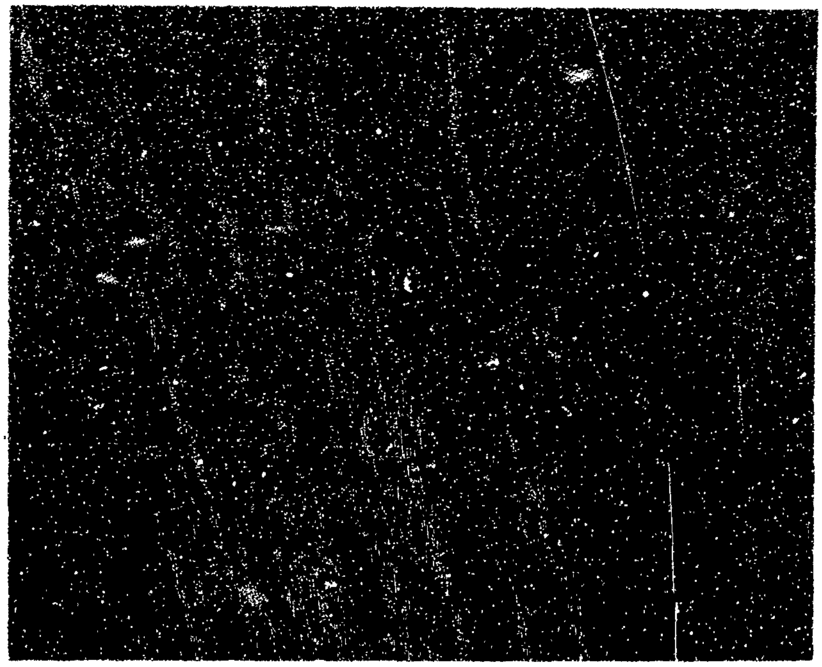


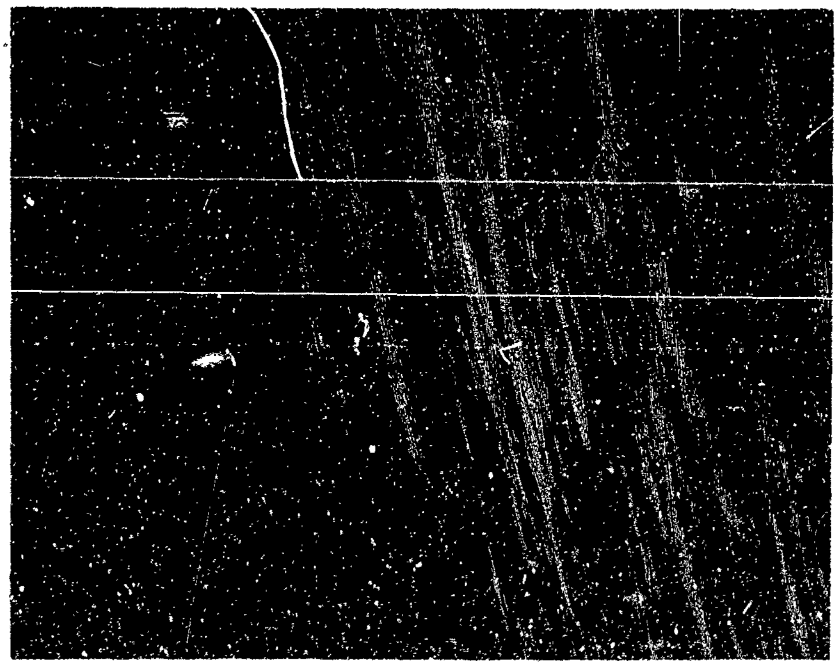
Figure 14. Results of Hardness Surveys Over the Thickness of Selected Overaged-and-Rolled 7075 Blocks.

examination was performed at two depths in block C4R: the first, at a rolling surface and the second, approximately midway between the two rolling surfaces. The microstructures at the two depths were found to be indistinguishable. Typical micrographs are shown in Figure 15.

<u>Thin-Film Electron Microscopy.</u> Thin films were also prepared from two different depths in block C4R. No difference in microstructure at the two depths could be found. A typical electron micrograph is shown in Figure 16. The difficulty of resolving dislocations, which must be present from the working operation, is again a surprising feature.



Rolling Surface



Midway Between Two Rolling Surfaces

Figure 15. Light Micrographs Taken at Two Different Depths of Overaged-and-Rolled 7075 Alloy (Block C4R). Plane of Both Specimens is Parallel to Rolling Plane (Etchant 2 Vol. % Aq. HF; Magnification 200X).

DISCUSSION

Of the two methods employed in this study to strengthen overaged 7075, press orging was the more effective. Greater strengthening was obtained in th center of a 4-inch-thick section using forging than in the center of a 3-inch section using rolling.

The reason for using a 4-inch-thick starting section for forging was dictated more by considerations of test specimen size and estimates of the reduction that would be required to obtain the desired strength level than it was by the actual incidence of such thick sections in industrial applications. A 2-inch-long stress-corrosion specimen was used because it conformed with available test fixtures, and a 50-percent reduction was anticipated when hand forgings were ordered measuring 4 inches in the short transverse direction. It was found that a 25-percent forging reduction was the tolerable maximum before cracking or a recrystallization-like phenomenon took place. It is possible that if a thinner starting section and a shorter specimen had been used, the desired strength level could have been achieved.

This brief study has demonstrated that an incremental loss of strength due to overaging can be completely regained, if the overaging has been performed between 50 and 400 hours at 350 F. At shorter overaging times, the strain hardoning mechanism cannot keep pace with the overaging mechanism that produces softening (Fig. 5). Thus, using the techniques described herein, there is a ceiling of ~65,000 psi on the yield strength, which may be obtained by starting with material in the -T73 temper (overaged 10 hrs. at 350 F).

If the program is to be continued along the present lines--i.e., combining various heat treatments with conventional deformation of the overaged material resulting from the heat treatment--it becomes necessary to explore ways of increasing the strain hardening at short overaging times. The main difficulty seems to be in producing uniform strain hardening before superficial cracking occurs. An unconventional deformation technique such as explosive shock loading would be more successful in this respect; however, there are still practical problems to be solved in connection with this method. Among the conventional techniques, a low energy rate process such as press forging would be superior to a faster process such as impact forging; and, as the present study has shown, press forging is superior to rolling. Having selected a promising metal working process, the next step might be to take advantage of different work hardening characteristics possessed by the different overaged conditions and devise some sequence of thermal-mechanical operations which would allow the internal strain hardening in a workpiece to keep pace with the external or more superficial strain hardening.

The present study has provided additional evidence for the negligible effect of strain hardening on stress-corrosion resistance. Not a single failure of overaged-and-forged or of overaged-and-rolled material was obtained within 30-day testing periods. The outstanding problem then is to increase the strength of inherently resistant material to a level of 70,000 psi or more.

CONCLUSIONS

1. Press forging is more effective than rolling in increasing the strength of overaged 7075.

2. Press forging is least effective for 7075 that has been overaged for less than 50 hours at 350 F.

3. The forging or rolling of 7075 that has been overaged for 20 hours or more at 350 F has no effect on the stress-corrosion time-to-failure within a 30-day testing period.

4. The best combination of yield strength and stress-corrosion time-to-failure that can be produced by overaging and forging appears to be ~65000 psi/> 30 days.

FUTURE WORK

A follow-on program will be conducted which has the same objectives as the present program. Instead of using starting material that has been overaged according to standard procedures, the starting material will be unconventionally heat treated 7075 containing $MgZn_2$ particles of carefully controlled size and distribution and varying concentrations of excess vacancies. One or more forging reductions will be included in the processing. Tensile and stress-corrosion tests will be conducted to establish the optimum heat treat variables. The use of starting sections, 3 inches or less in the short transverse direction, and stress-corrosion specimens, which are less than 2 inches in the same direction, will be considered whenever a forging operation is required.

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